

# 'Photosynthetic' Quantum Computers?

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August 19, 2001

## Abstract

Do quantum computers already exist in Nature? It is proposed that they do. Photosynthesis is one example in which a 'quantum computer' component may play a role in the 'classical' world of complex biological systems. A 'translation' of the standard metabolic description of the 'front-end' light harvesting complex in photosynthesis into the language of quantum computers is presented. Biological systems represent an untapped resource for thinking about the design and operation of hybrid quantum-classical computers and expanding our current conceptions of what defines a 'quantum computer' in Nature.

## 1 Introduction

It was recently expressed at the **Quantum Applications Symposium (Ann Arbor, MI, July 1-3, 2001)** during a panel discussion that there were no examples of 'quantum computers' in nature. This author would like to point out that there are quantum computers everywhere and our lives depends on them.

We begin with a brief description of what we mean by 'quantum logic gates' and 'quantum computers' in general. Any system in which a 'quantum' signal such as a photon, exciton, phonon, fundamental particle, atom and even molecule (in special cases) is 'input' or 'detected' and is then 'processed' or 'computed' into one or more 'output' or 'emitted' quantum or 'classical' signals is a quantum logic gate. If the input signal is held for later use, then the 'gate' can be a quantum information 'register', 'accumulator' or 'memory'. The combination of logic operations *on* an **info-state** created by the detected 'signal' and its storage in memory can be properties of a

single physical 'gate'. New info-states (and therefor 'information') can be created by logic (physical) operations on other info-states in these 'gates'. An 'info-state' in this paper is the general *state* of any system with any kind of 'information content'. The content of the information is a physical property of the system such as the energy or geometric configuration. The content of a gate is the configuration information for the excited state capable of creating a signal upon reconfiguration.

This gate may be a set of quantum logic gates acting as a single quantum logic gate which we call a Collective Excitation Network or CEN [11]. A quantum computer is any system which can process 'quantum' (or 'classical') signals and quantized information states into one or more quantum signals or classical states. The flow of quantum information through a given sequential pathway of gates and connections in a causal network creates a Sequential Excitation Network or SEN [1]. Causal networks are SENs in which 'output' information is created by the reconfiguration processes of unstable or 'triggered' states of 'gates'. These nodes in the network are the local '*cause*' (source or Feynman Clock [10]) components. The signals propagate in the vacuum or along restricted permanent or temporary physical pathways ('circuits') to detectors that convert the signals info-state into a local '*effect*' (excited state of the Feynman Clock detector or quantum logic gate) in a sequential 'history'.

The 'time' associated with the quantum information flow in quantum computers is created by 'time labeling' states of gates by pairing them with standard clock 'quantum' signals in a process called 'signal mapping' [2] by a time or '**T-computer**' [3]. The T-Computer can be a 'front-end' quantum computer that can be controlled by an observers 'classical' computer. It can be used to time label 'cause-effect' relationships between qubits, qwords (coupled sets of qubits) and classical bits and words in shift and memory registers. The details of quantum 'clocks' for quantum computers are being investigated by the author.

Examples of natural 'quantum computers' include the retinal photodetectors (vision) in animals [4] and the light harvesting or 'antennae' apparatuses in plants and some bacteria [5], [6], [7], [8], [9]. Components of these detection systems act as quantum or Feynman Clock logic 'gates' detecting incoming 'signals', processing them, and creating output signals that propagate energy and information in metabolic causal networks [10], [11], [1]. We will focus on the 'quantum computer' aspects of a highly simplified model of 'Phase I reactions' [5] in the membranes of photosynthetic units or PSUs in plants as an example. PSUs are 'causal networks' acting as 'quantum' and chemical energy 'ladder' computers processing photons into output signals

such as excitons, electrons, ions and 'energy' transfer molecules like ATP.

The 'computation' of photons into bioavailable energy begins with the conversion of photons into 'exciton' resonances in the light harvesting antennae. These exciton signals are then sent along the 'wiring' of the PSU as electron 'currents' between molecular structures. The continued energy flow in the PSU represents a flow of information that is transformed into various kinds of 'signals' such as ions and molecules in excited states by the 'logic' of the biochemical structure of the PSU computer. The question of whether or not energy transfers in the later stages of photosynthesis is a 'quantum' or 'classical' process depends on the signal type. Chemical signals generally fall into a 'classical' description if quantum mechanics is not necessary to characterize the physical state of the signal and the system with which it is interacting. The processing of 'quantum information' by living systems is one of the foundations for the field of quantum biology.

At the computational nodes in the photosynthetic causal network where chemical or physical transport of energy can be described without quantum mechanics, we see a classical computational model may be more effective. Careful examination of the quantum to classical transition at the mesoscopic scale represent opportunities for designing novel hybrid biological and physical/chemical interfaces between quantum and classical computers. In a complex system like the purple bacteria, we see a mix of both quantum and classical computer elements depending on the mechanism of energy (information) transfer. The complex interactions of 'signals' with 'noise' in these hybrid biological quantum-classical information processing systems raises issues of metabolic efficiency of both initial signal detection and subsequent 'logic' operations performed on the information flowing through causal networks in complex systems [12], [13].

The propagation of information via different forms of signals in a causal network tells us that signals and their information content can take various 'quantum' as well as 'classical' forms. This opens the possibilities of looking at quantum computing systems in the broader context of biological systems. The detection of single photons by the eye [4] entails 'computation' of both spectral and geometric (spatial and motion) information from the 'observed' system. The photon detectors in the retina act as 'front end' quantum computers linked to the 'classical' neural network of the optic nerve and visual cortex in the brain. Front end 'quantum detectors' and 'computation' systems are one of nature's fundamental solutions to the problem of survival by providing living systems with a high sensitivity to environmental data.

## 2 Photosynthesis and the 'Computation' of Photons into Bio-Energy

There are many ways to transfer energy and therefore 'information' as signals originating in unstable or excited quantum systems (Feynman Clocks) such as atoms and molecules. These include Excitons, Luminescence, Physical Quenching, Ionization, Dissociation, Direct Reaction Charge Transfer, Isomerization, Inter-molecular energy transfer, Intra-molecular Radiationless transition energy transfer, and Phosphorescence [14]. In the case of photosynthesis, the 'final' signal we will examine is the ATP molecule. ATP represents the energy 'source' for the production of glucose and oxygen which are essential for '*chemotrophs*' like us.

The light harvesting molecular antennae in the PSU of 'phototrophs' (algae, plants and photosynthetic bacteria) detect photons and convert them directly into usable energy for the organism via the synthesis of ATP. ATP fuels the metabolism of phototrophic cells which includes the synthesis of large amounts of sugars like glucose. The glucose can be further processed by polymerization into storage macromolecules such as starch and cellulose used in cell walls. These molecules can in turn be used as energy sources for ATP in photosynthetic cells of most bacterial species, protozoa, fungi, and animal cells by 'digestion'. We can see that we are intimately connected to the quantum world of photons through the myriad of complex causal networks we call 'life'.

### 2.1 The 'Quantum Computer' Component of PSUs

Photosynthesis is part of the 'energy processing' causal network essential to all life [9]. The conversion of starlight into usable biological energy begins with photosynthesis in '*phototrophs*' [5]. The simplified model used here does not account for real details such as the cyclic behavior of complex chemical pathways controlled by feedback mechanisms.

Photon absorption triggers atomic and molecular reconfigurations. These changes can be expressed as different types of physical and chemical processes. Some of the energy conversions occur by dissociation ionization, direct reactions, charge transfer, excitons, isomerization, intermolecular energy transfer, intramolecular or radiationless transfer, luminescence, fluorescence, phosphorescence, diffusion, physical quenching, resonant chain reactions (SENs), internal conversion (e.g. decoherence) and 'thermal' effects in unstable systems [14].

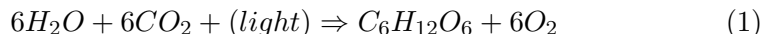
We will now briefly outline a *simplified* version of the photosynthetic

quantum computer (PQC) components of the 'purple bacteria' as an example. A 'translation' of the standard metabolic descriptions of the photosynthetic apparatus in the intracytoplasmic membrane of purple bacteria [6] into quantum computer notation[15],[16], [17], is given below.

**Excitation transfer in the PSU of the Purple Bacteria** starting with photon detection resulting in exciton signals propagating along the quantum computer network to the RC 'quantum/classical' processing 'gate'.

The photon and exciton signals can be described with quantum mechanics applied to electronic excitation in the PSU energy ladder. The following equations are only illustrative of the **intercomplex** process of energy and information transfer *between* the complexes and the exact details of the **intracomplex** 'computation' processes *inside* the membrane '*gates*' of the PSU computer are beyond the scope of this paper. The reader can find excellent information at the following web pages: <http://www.ks.uiuc.edu/> and <http://www.life.uiuc.edu/govindjee/paper/gov.html>

The overall 'classical' *chemical* equation of photosynthesis for plants is [5]:



We will focus on the reactions in the well studied purple bacteria (e.g. Rhodobacter (Rb.) sphaeroides) to illustrate the '*front end*' quantum computer aspects of the generally 'classical' energy transfer processes in the remainder of the photosynthetic causal network leading to the conversion of ADP into ATP.

The process begins with the detection of photons which are resonantly absorbed by light harvesting complexes in the membrane of the PSU. For purple bacteria, these can be any one or a combination of primary resonances. The PSII complex can detect photons at 800 and 850 nm by **bacteriochlorophylls (BChls)**. It can also detect 500 nm photons with the lycopene or carotenoid backbone supporting the B800 and B850 BChl detector sites. The intracomplex carotenoid detection of photons is too complex to describe here and will only be mentioned. For more details, see [18].

We will look at a *simplified* metabolic pathway involving the detection of an 800 or an 850 nm photon. We will also ignore the photon detector 'accumulator' or 'register' function of the complex in building an **exciton** resonance by the complex with many (8 or more?) separate detections. The *intercomplex* transmission of energy is from one complex to another interior **LHII** or **LHI** complex on its way to the **reaction center (RC)**. The LHI complex can also detect photons at 875 nm.

The **RC** represents the site or 'gate' where *quantum information* is converted into *classical chemical information*. The purpose of this paper is to suggest how we may think about the biological processing of photons into life energy as having 'quantum' as well as 'classical' computer aspects. The subtle details of 'quantum biology' demand a much more careful treatment that can be given here. The reader is asked to see the references for such a treatment.

### 2.1.1 A Simple Example of 'Front-end' Quantum Computer 'Logic' in the PSU of Purple Bacteria

We will look at the maximum information path in the PSU from the detection of an 800 or an 850 nm photon by an outer LHII. The energy/signal will be transferred to an inner LHII by an 'exciton'. This inner LHII will then transfer the exciton to the LHI. The LHI will then transfer the energy/signal to the reaction center, RC, where it is converted into 'available' energy as electron-hole separation for the 'quantum' processing of  $\mathbf{H}^+$  ions (protons) and electrons with a 'classical' binding of cytoplasmic **quinone**,  $\mathbf{Q}_B$ , to the **RC**. The  $\mathbf{Q}_B$  is reduced to hydroquinone,  $\mathbf{Q}_B\mathbf{H}_2$ , and then released.

The  $\mathbf{Q}_B\mathbf{H}_2$  is then processed by the **bc**<sub>1</sub> complex in an exothermic reaction that pumps protons across the membrane into the periplasm. During this operation, electrons are transmitted to the **RC** from the **c**<sub>2</sub> cytochrome complex on the periplasmic side to the **bc**<sub>1</sub> to the **c**<sub>2</sub> 'gate' on the periplasmic side to the **RC**.

The electron transfer across the membrane induces a proton gradient that drives the 'classical' synthesis of **ATP** from **ADP** at the **ATPase** 'gate'. This is the point at which energy for other complex 'life' processes becomes 'classically' or chemically available.

The detection of the photon,  $|\lambda_{II}^{(2)}\rangle$ , by an outer LHII complex resulting in an excited state,  $|LHII_*^{(2)}\rangle$ , is represented by:

$$|\lambda_{II}^{(2)}\rangle + |LHII_0^{(2)}\rangle \implies |\lambda_{II}^{(2)}\rangle \otimes |LHII_0^{(2)}\rangle = |LHII_*^{(2)}\rangle \quad (2)$$

After the needed number of photons are detected, the excited state of this LHII Complex represents the *collective state* of an **intracomplex** network of the individual Feynman Clocks (B800, B850, and lycopene FCs) which 'decays' in a 'finite lifetime' (computed using a T-computer time labeling process or the like) with the creation of an *exciton signal*.

Next we have the 'decay' of this info-state and the creation of an exciton,  $|\epsilon_{II \rightarrow II}\rangle$ , which transfers information to the inner LHII complex:

$$|LHII_*^{(2)}\rangle \Rightarrow |LHII_0^{(2)}\rangle \otimes |\epsilon_{II \rightarrow II}\rangle \Rightarrow \quad (3)$$

$$|LHII_0^{(2)}\rangle + |\epsilon_{II \rightarrow I}\rangle \Rightarrow |LHII_0^{(1)}\rangle \otimes |\epsilon_{II \rightarrow II}\rangle \Rightarrow |LHII_*^{(1)}\rangle \quad (4)$$

The excited state of the inner LHII decays or transfers the energy in a similar manner to the LHI. We have:

$$|LHII_*^{(1)}\rangle \Rightarrow |LHII_0^{(1)}\rangle \otimes |\epsilon_{II \rightarrow I}\rangle \Rightarrow |LHII_0^{(1)}\rangle + |\epsilon_{II \rightarrow I}\rangle \quad (5)$$

$$\Rightarrow |\epsilon_{II \rightarrow I}\rangle \otimes |LHI_0\rangle \Rightarrow |LHI_*\rangle \quad (6)$$

The inner LHI excited info-state provides the information for the creation of an exciton signal that propagates inward to the RC:

$$|LHI_*\rangle \Rightarrow |LHI_0\rangle \otimes |\epsilon_{I \rightarrow RC}\rangle \Rightarrow |LHI_0\rangle + |\epsilon_{I \rightarrow RC}\rangle \quad (7)$$

$$\Rightarrow |\epsilon_{I \rightarrow RC}\rangle \otimes |RC_0\rangle \Rightarrow |RC_*\rangle \quad (8)$$

Now we see how the original photon signal information has propagated alternating between 'free' signals and info-states of complexes delivering energy and information to the RC. In summary, the photon has been processed into an unstable info-state of the outer LHII, then into an inwardly propagating *exciton signal* down the 'energy ladder'. This is followed the excitons detection by an inner LHII which is creates an unstable info-state of that LHII complex. This info-state is processed into another (in the case of direct transfer, the first and second excitons between LHIIs can be considered the 'same') exciton signal which propagates to the LHI complex. This creates an unstable info-state of the LHI which in turn decays into a ground state by the transfer of information via an exciton to the inner RC core of the LHI. The 'excited' state of the RC is where the 'output' signal of this front-end quantum computer meets the 'classical' chemical computer components that further process the original photons information into the chemistry of 'life'.

We can see that the distinction between quantum photon and exciton processes and classical 'chemical' processes becomes 'fuzzy' in the **RC**. The transport of electrons and protons can be treated classically when their gate to gate path-lengths are much larger than the size of the systems in which

they are 'processed' or 'generated'. The 'chemical' processes reflect the fact that the transfer of energy and information is mediated by 'mobile' systems whose physical scale with respect to the quantum information content allows it to be described with classical physics. This can be thought of as classical if the magnitude of the 'action',  $\mathbf{A} = |\vec{\mathbf{p}} \cdot \vec{\mathbf{r}}| = \mathbf{E} \cdot \mathbf{t}$  involved with the 'signal' and 'detector' interaction is  $\mathbf{A} \gg 1.05457266 \times 10^{-34} \text{ J s} = \hbar$  [20].

### 2.1.2 'Time' and Info-flow in Quantum Computers

The *state information* is transferred from gate to gate as an '**info-state**'. The creation of a new info-state in a gate can be 'time labeled' using the signals from a standard clock by a method of 'signal mapping' with a **T-computer** [3]. Clock signals can also be used to 'drive' computational processes.

The quantum arrows of time or QATs are 'constructions' built from information originating in the Feynman Clock (FC), Collective Excitation Network (CEN) and quantum Sequential Excitation Network (SEN) [1] processes in a cell and 'computed' into 'time labels' by the observing system or a higher order computing system of which the quantum computer is a part. The quantum computer components of the PSU represent the building blocks of larger biological networks such as trees with their energy and chemical fluid transport systems creating daily and seasonal 'arrows of time' for overall complex system configurations of a superposition of various metabolic causal networks. This model can be generalized to the information processing quantum and classical computers in animals. The control and transport systems are hierarchically built upward in systematic complexity with benchmark plateaus of complexity at the cellular and organ level to support the activities of the central nervous system and the brain.

## 2.2 The Creation of Novel Information States and the 'Conservation of Information Law'

Biological system are distinct from other evolving systems such as galaxies, stars and planets in that they can process information and create novel and complex forms of information embodied in 'hand-made' physical systems and artifacts. The overall flow of information in the universe is driven by stellar evolution. How is it that new forms of information can be created from evolving physical systems? How do these new info-states of material systems arise? Are they computed from previous info-states in conjunction with some sort of information 'reservoir' of other info-states in order to account



for the differences between the initial and final configurations of a system? We can look at the possibility that if there is a 'Conservation of Information Law' [19] for the entire universe that new info-states are computed using other local info-states (signals) and the expanding 'vacuum' of space as a reservoir of information vastly larger (in direct proportion to the total mass of the dark energy or missing mass) than the 'visible' astronomical objects we observe. A general conservation of information law will offer a vantage point to 'account' for the information content and novelty of evolving physical systems while addressing question of non-local information entanglement in quantum computers of biological and condensed matter origins. It may also be useful in designing future hybrid quantum and classical computer systems by providing a means for accounting for all information involved in complex computational processes.

### 3 Hybrid Quantum-Classical Computers?

If we stay within the domain of the 'physics' approach to quantum computation as an extension of the solid state approach to classical large scale computers, then we are overlooking the opportunity to introduce the adaptive and quasi-analog properties that biological quantum computers offer.

### 4 Acknowledgments

Special thanks to **Steven Behr** for valuable discussions about the ideas in this paper during and after our attendance at the Quantum Applications Symposium. Thanks to Toni H. for her valuable 'time'.

### 5 Bibliography

#### References

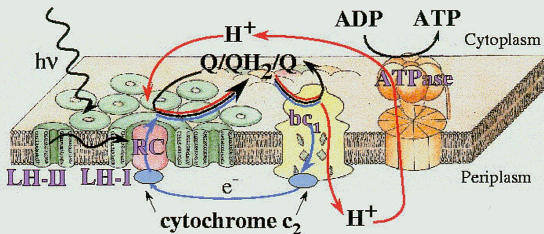
- [1] **"Feynman Clocks, Causal Networks, and Hierarchical Arrows of Time in Complex Systems From the Big Bang to the Brain"** An invited talk and paper given by *Scott Hitchcock* at the 'XXIII International Workshop on the Fundamental Problems of High Energy Physics and Field Theory' at the Institute for High Energy Physics (IHEP), Protvino, Russia, June 21-23, 2000. Published in the Proceedings of the Workshop and as

NSCL as pre-print (MSUCL -1172). It is also at the Los Alamos National Labs, LANL e-Print Archives report number quant-ph/00100014. A PDF version is available and can be downloaded from; [http://www.nsl.mscl.edu/news/nsl\\_library/nsl\\_preprint/MSUCL1172.pdf](http://www.nsl.mscl.edu/news/nsl_library/nsl_preprint/MSUCL1172.pdf)

- [2] **"Time and Information: Part 1"** by *Scott M. Hitchcock*, at the Los Alamos National Labs, LANL e-Print Archives report number quant-ph/0012017, 12/6/00 and at NSCL as pre-print (MSUCL-1183). A PDF version is available and can be downloaded from; [www.nsl.mscl.edu/news/nsl\\_library/nsl\\_preprint/MSUCL1183.pdf](http://www.nsl.mscl.edu/news/nsl_library/nsl_preprint/MSUCL1183.pdf)
- [3] **"Time and Information: From Feynman Diagrams to Feynman Clocks and Beyond..."** An invited talk and paper given by *Scott Hitchcock* at the XXIV 'Time' International Workshop on the Fundamental Problems of High Energy Physics and Field Theory at the Institute for High Energy Physics (IHEP), Protvino, Russia, June 27-29, 2001. To be published in the Proceedings of the Workshop. A preliminary schematic of the **T-computer** is at <http://www.nsl.mscl.edu/departments/facilities/hitchcock/index.htm>
- [4] **"Single-photon detection by rod cells of the retina"** by *F. Rieke* and *D. A. Baylor*, Reviews of Modern Physics, Vol. 70, No. 3, July 1988, pp. 1027-1036.
- [5] **"Cells"**, by *David M Prescott*, Jones and Bartlett Publishers, Boston, 1988.
- [6] **"From Simplicity to Complexity and Back: Function, Architecture, and Mechanism of Light-harvesting Systems in Photosynthetic Bacteria"** by *K. Schulten*, from 'Simplicity and Complexity in Proteins and Nucleic Acids', edited by H. Frauenfelder, J. Deisenhofer, and P. G. Wolynes, Dahlem University Press, 1999.
- [7] **"Excitons and excitation transfer in the photosynthetic unit of purple bacteria"** by *Thorsten Ritz*, *Xiche Hu*, *Ana Damjanovic*, and *Klaus Schulten*, Journal of Luminescence, 76 & 77 (1998) 310-321.
- [8] **"Kinetics of Excitation Migration and Trapping in the Photosynthetic Unit of Purple Bacteria"** by *Thorsten Ritz*, *Sanghyun Park* and *Klaus Schulten*, Journal of Physical Chemistry B, 2001. In Press.

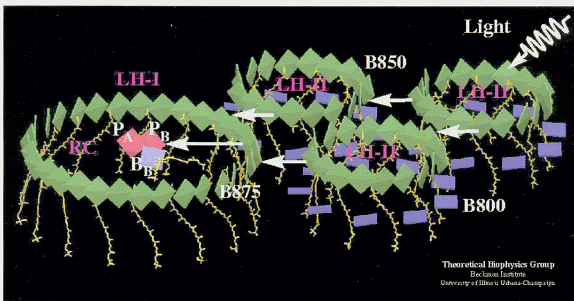
- [9] **"The Photosynthetic Process"** by *John Whitmarsh* and *Govindjee*, published at <http://www.life.uiuc.edu/govindjee/paper/gov.html>
- [10] **"Quantum Clocks and the Origin of Time in Complex Systems"** by *Scott Hitchcock*, LANL e-print archives; gr-qc/9902046 v2, 20 Feb 1999, also NSCL Publication: MSUCL-1123, 1999. A PDF version is available and can be downloaded from; [http://www.nsl.msui.edu/news/nsl\\_library/nsl\\_preprint/MSUCL1123.pdf](http://www.nsl.msui.edu/news/nsl_library/nsl_preprint/MSUCL1123.pdf)
- [11] **"Feynman Clocks, Causal Networks, and the Origin of Hierarchical 'Arrows of Time' in Complex Systems from the Big Bang to the Brain. Part I 'Conjectures'"** by *Scott Hitchcock*, LANL e-print archives; gr-qc/0005074, 16 May 2000, also NSCL Publication: MSUCL-1135, 2000. A PDF version is available and can be downloaded from; [http://www.nsl.msui.edu/news/nsl\\_library/nsl\\_preprint/MSUCL1135.pdf](http://www.nsl.msui.edu/news/nsl_library/nsl_preprint/MSUCL1135.pdf)
- [12] **"Metabolically Efficient Information Processing"** by *Vjay Balasubramanian*, *Don Kimber*, and *Michael J. Berry II*, LANL e-print archives, con-mat/0105127, 6 May 2001.
- [13] **"Metabolically Efficient Codes in the Retina"** by *Vjay Balasubramanian* and *Michael J. Berry II*, LANL e-print archives, con-mat/0105128, 6 May 2001.
- [14] **"Photochemistry"** by *Carol E. Wayne* and *Richard P. Wayne*, Oxford University Press, England, 1996.
- [15] **"Explorations in Quantum Computing"** by *Colin P. Williams* and *Scott H. Clearwater*, Springer-Verlag, New York, 1998.
- [16] **"Lecture Notes for Physics 229: Quantum Information and Computation"** by *John Preskill*, California Institute of Technology, September 1998, available at <http://www.theory.caltech.edu/~preskill/ph229>.
- [17] **"Quantum Computation and Quantum Information"** by *Michael A. Nielsen* and *Isaac L. Chuang*, Cambridge University Press, UK, 2000.
- [18] **"Architecture and mechanism of the light-harvesting apparatus of purple bacteria"** by *Xiche Hu*, *Ana Damjanovic*, *Thorsten Ritz*, and *Klaus Schulten*, Proc. Natl. Acad. Sci. USA, Vol. 95, pp. 5935-5941, May 1998.

- [19] "**Is There a 'Conservation of Information Law' for the Universe?**" by *Scott Hitchcock*, LANL e-print archives; gr-qc/0108010, 3 Aug 2001, <http://xxx.lanl.gov/abs/gr-qc/0108010>.
- [20] "**Basic Quantum Mechanics**", by *Robert L. White*, McGraw-Hill Book Company, New York, 1966.



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**Figure 1.** The figure represents the scheme of the integral membrane proteins forming the photosynthetic unit. Light-absorption and excitation transfer within the light-harvesting proteins (LH-II and LH-I) are represented by wavy lines. Electron transfer within the photosynthetic reaction center (RC), cytochrome  $c_2$ , and  $bc_1$  complex is represented by blue lines. Proton transfer in the  $bc_1$  complex and the ATPase is represented by red lines. The chemical reaction resulting in ATP synthesis is represented by a black line. Figure courtesy of UIUC.  
[http://www.ks.uiuc.edu/Research/quantum\\_biology/](http://www.ks.uiuc.edu/Research/quantum_biology/)



**Figure 2.** This figure illustrates the energy transfer from photon detection sites through the causal network of the bacterial photosynthetic unit. LH-II contains two types of BChls commonly referred to as B800 (dark blue) and B850 (green) which absorb at 800 nm and 850 nm respectively. BChls in LH-I absorb at 875 nm, and are labeled as B875 (green).  $P_A$  and  $P_B$  refer to the reaction center special pair, and  $B_A$ ,  $B_B$  to the accessory bacteriochlorophylls. The figure exhibits clearly the co-planar arrangement of the B850 BChl ring in LH-II, the B875 BChl ring of LH-I, and the reaction center BChls  $P_A$ ,  $P_B$ ,  $B_A$ ,  $B_B$ . We note that the white arrows indicate the physical path in space of information flow and ‘infostate’ propagation from the LHII complexes towards the RC inside the LH-I ring. The transfer mechanism is by exciton resonance of the LHII complexes. At each stage of information transfer through this network, the active infostate representing the propagating information is localized in such way that previous nodes on the network are classically separated. Figure courtesy of UIUC.  
[http://www.ks.uiuc.edu/Research/psu/psu\\_inter.html](http://www.ks.uiuc.edu/Research/psu/psu_inter.html)

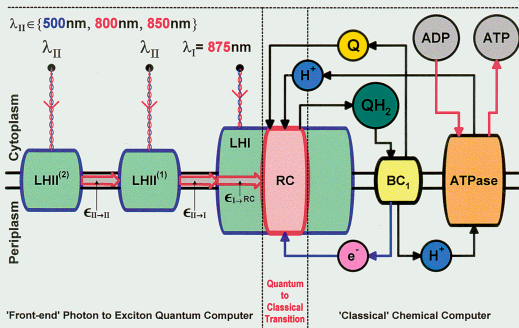


Figure 3. The network representation of the 'front-end' quantum computer and the classical computer components of the PSU.